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CONSTRAINTS ON GALAXY FORMATION FROM STARS IN THE FAR OUTER DISK OF M31[1]

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ABSTRACT

Numerical simulations of galaxy formation within the cold dark matter (CDM) hierarchical clustering framework are unable to produce large disk galaxies without invoking some form of feedback to suppress gas cooling and collapse until a redshift of unity or below. An important observational consequence of delaying the epoch of disk formation until relatively recent times is that the stellar populations in the extended disk should of be predominantly young-to-intermediate age. We use a deep HST/WFPC2 archival pointing to investigate the mean age and metallicity of the stellar population in a disk-dominated field at 30 kpc along the major axis of M31. Our analysis of the color-magnitude-diagram reveals the dominant population to have significant mean age ($\gtrsim$ 8Gyr) and a moderately-high mean metallicity ([Fe/H]~ -0.7); tentative evidence is also presented for a trace population of ancient (≥ 10 Gyr) metal-poor stars. These characteristics are unexpected in CDM models and we discuss the possible implications of this result, as well as alternative interpretations.

Subject headings: galaxies: individual (M31) — galaxies: formation and evolution — galaxies: spiral — stars: Hertzsprung-Russell diagram — stars: Population II

1. INTRODUCTION

It is generally believed that galactic disks form from baryons which cool and dissipatively collapse inside the potential wells of tidally-torqued dark matter halos. Under the assumption that the gas component retains most of its initial angular momentum, this process leads to systems with sizes and collapse times compatible with present-day large disk galaxies (*eg.* Fall & Efstathiou 1980). However, numerical simulations of galaxy formation within the popular cold dark matter (CDM) hierarchical clustering framework indicate that this condition is far from being satisfied. The merging process inherent in this picture leads to efficient outward transport of angular momentum from the collapsing gas to the dark halo, resulting in final disks which have specific angular momenta an order of magnitude too small (*eg.* Navarro & Steinmetz 1997).

A possible solution to this "angular momemtum problem" is to suppress gas cooling and collapse until late times, when the most active phase of merging is over. Various papers have shown that if strong feedback from an early generation of stars can delay the epoch of disk formation to z$\lesssim$ 1 then systems can form by the present-day with angular momenta compatible with observations (*eg.* Weil, Eke & Efstathiou 1998; Sommer-Larsen, Gelato & Vedel 1999; Binney, Gerhard & Silk 2001).

While delayed disk formation is a promising solution to the angular momentum problem, one must ask whether such a scenario is compatible with the age distribution of stars in present-day disks. For a flat Universe with $\Omega_\Lambda = 1 - \Omega_{matter} = 0.7$ and $H_o = 65 - 75$ km s^{-1} Mpc^{-1}, a redshift of unity corresponds to a lookback-time of 7–8 Gyr. Binney, Dehnen & Bertelli (2000) recently determined the ages of the oldest thin disk stars in the Hipparcos sample to be ≈11 Gyr, on a scale where the halo globular clusters are 12 Gyr old, although they state that maximum ages as low as 9 Gyr are plausible. Adopting this as a lower limit to the age of the Milky Way disk, one infers that at least some fraction of the local thin disk – corresponding to 8 kpc in radius, or ~ 3 exponential scalelengths – was in place by a redshift of ∼1.4 for a flat Universe cosmology. Extending these arguments to the local thick disk could push this redshift back to ~ 2 (*eg.* Wyse 2001).

While the local Galactic disk places an interesting constraint on the epoch of disk formation, it is clearly desirable to explore other localities and other galaxies. Indeed, the entire disk may not necessarily need to form late in delayed formation models; it is possible that a less extended disk was in place at early times, with the accretion of higher angular momentum material at later epochs (*eg.* Ferguson & Clarke 2001). A knowledge of the stellar populations at very large radii in galactic disks is therefore of particular importance.

This *Letter* presents the first results from a study to probe the fossil record in our nearest large neighbour, M31, through the analysis of deep, archival HST/WFPC2 pointings. We focus here on the color-magnitude-diagram (CMD) of a disk-dominated field in the far outer disk of M31 which proves to have potentially interesting implications for the formation epoch of large disk galaxies.

2. OBSERVATIONS & PHOTOMETRIC REDUCTION

The M31 globular cluster G327 was targeted with HST/WFPC2 as part of program GO6671. Exposure

[1]Based on observations with the NASA/ESA Hubble Space Telescope, obtained from the data archive of the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract No. NAS5-26555.

times of 5300 and 5400s were obtained in filters F555W and F814W, respectively. Due to an error in coordinates, the actual telescope pointing (PC centered on $\alpha_{2000} = 00^h49^m36.2^s, \delta_{2000} = 43°01'07''$) was some distance from G327 and placed the field along the north-west major axis at a radial distance of $\sim$30 kpc, where we assume $m - M = 24.47 \pm 0.12$ (D=783 kpc; Durrell et al 2001). For M31 position angles in the range 35-40°, the WFPC2 field lies $\lesssim 5°$ from the major axis (see Figure 1). By extrapolating the structural parameters determined by Walterbos & Kennicutt (1988, hereafter WK88) and assuming an inclination of 12.5°, we expect that at this location – corresponding to approximately 5 exponential disk R-band scalelengths or 1.4 R_{25} – disk stars should contribute $\sim$ 95% of the stellar surface density.

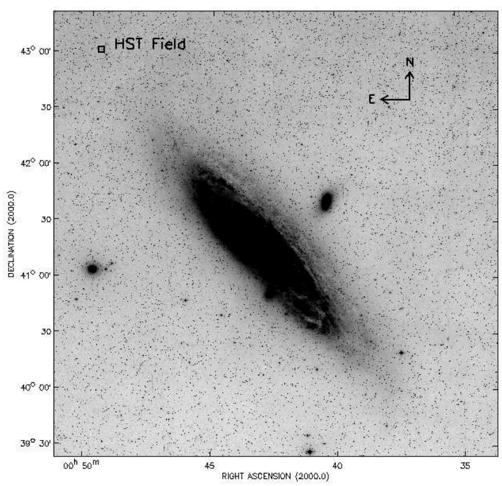

Fig.1 - A Palomar Sky Survey plate of M31 with the location of the HST field overlaid. The field size is 3.4° × 4.0°; the box indicating the WFPC2 pointing is not drawn to scale.

The data were retrieved from the Space Telescope-European Coordinating Facility archive and reprocessed with the most up-to-date calibration exposures. Due to the relative sparseness of the field, only the larger-area WF frames were considered. Images in a given filter were combined with a cosmic-ray rejection algorithm and Tiny Tim point-spread functions (PSFs) were fitted to the detected stars using the DAOPHOT/ALLSTAR crowded-field photometry package (Stetson 1987). Stars detected in different filters were matched and the photometry lists were pruned to exclude objects which were either poorly fit by the PSF model or had large (ie. $\sigma \gtrsim 0.3$ mag) photometric errors. Aperture corrections were measured from stars on our frames and the synthetic transformations of Holtzman et al (1995) were applied to derive standard magnitudes. We adopt a foreground Galactic reddening of E(V−I)=0.10 toward M31 (Holland et al 1996); as the field lies a considerable distance from the center of the galaxy (albeit still within the low density outer reaches of the HI disk), no correction was made for internal reddening. Artificial star tests indicate a high level of completeness with $\gtrsim$ 75% of the stars returned for V $\sim$ 26.5, I $\sim$25.5. Full details of the analysis procedure will be reported elsewhere.

3. DISSECTING THE COLOUR-MAGNITUDE DIAGRAM

Figure 2 presents the (V,V−I) and (I,V−I) CMDs for the far outer disk field. The basic morphology is that of a predominantly old-to-intermediate age population; indeed the CMDs bear a striking resemblance to those of M31 *halo* fields studied previously with HST (*eg.* Rich et al 1996, Holland et al 1996) however the halo component is expected to be only a very minor contributor at this location. Contamination from foreground Galactic stars and background unresolved galaxies is expected to be negligible in WFPC2 fields along the M31 sightline (see Holland et al 1996, Ferguson et al 2000).

3.1. *The Red Giant Branch*

The most prominent features in the CMD are the red giant branch (RGB), and the red clump (RC) which is superposed on the RGB at V $\sim$ 25.3, I $\sim$ 24.3. Together, these features contain more than 95% of the total number of stars detected in the WFPC2 field above the 75% completeness level. The mere existence of these features in the CMD attests to the presence of a population(s) with age(s) in the range $\sim 2 - 10$ Gyr.

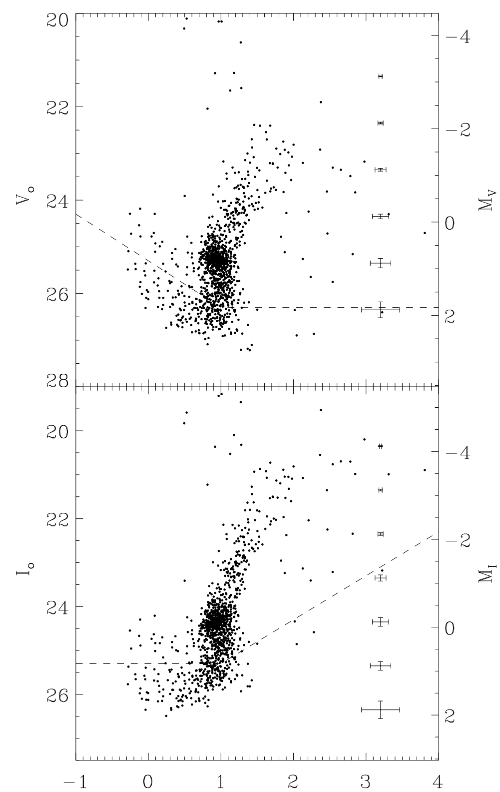

Fig.2 - The (V,V−I) (top) and (I,V−I) (bottom) CMDs for stars at large radius along the major axis of M31 on the standard Johnsons-Cousins system. Stars from all three WF chips are plotted. The dashed line indicates the 75% completeness level as determined from fake star tests. A distance modulus of 24.47 and a reddening of E(V-I)=0.10 (Holland et al 1996) have been used to transform to absolute magnitudes and unreddened colors.

The RGB V-I color is rather insensitive to ages $\gtrsim$ 2 Gyr, but is more sensitive to metallicity, as demonstrated in Figure 3 which shows fiducial RGBs for Galactic globular clusters overlaid on the (V,V−I) CMD. The M31 outer

disk RGB is well-matched in the mean by the ridge line of 47 Tuc, the prototypical metal-rich globular cluster with [Fe/H]$= -0.71$ on the Zinn & West (1984) scale. Very few stars are visible above the tip of the giant branch. The significant color width of the RGB detected here (~ 1 mag at V ~ 23) exceeds that of photometric errors, and is most easily explained by an intrinsic spread in metallicity of the stellar population. Assuming an old, nearly coeval population, the comparison with globular cluster fiducials indicates the metallicity spread could be as large as ~ 2 dex. On the other hand, a mono-metallicity population with [Fe/H]$= -0.7$ would, using the Girardi et al (2000) isochrones, have a maximum RGB width of only $\lesssim 0.4$ mag for an age range of 0.5–16 Gyr. It therefore appears that the relatively high metallicity and intrinsic dispersion which has been previously shown to characterise the M31 field halo (*eg.* Mould & Kristian 1986; Holland et al 1996; Rich et al 1996; Durrell et al 2001) also characterises the far outer disk.

3.2. *The Red Clump*

The color and luminosity of a core He-burning star depends on its age, metallicity and He content. Several recent papers have highlighted the potential power of the red clump (RC), when coupled with independent metallicity estimates, as an age indicator (*eg.* Cole 1999; Cole et al 1999; Girardi & Salaris 2001).

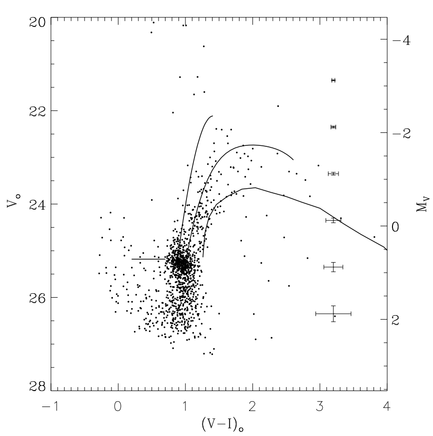

Fig.3 - (V,V−I) CMD for our M31 field with globular cluster fiducial sequences overlaid. From left to right, these correspond to the Galactic GCs NGC 6397 ([Fe/H]$= -1.91$), 47 Tuc ([Fe/H]$= -0.71$) and NGC 6553 ([Fe/H]$= -0.28$) and are taken from Da Costa & Armandroff (1990) and Sagar et al (1999). In the case of NGC 6553, we have assumed a distance modulus of 13.6 and a reddening of E(V−I)$= 0.95$ (Guarnieri et al 1998). Also indicated is the V magnitude of the extended horizontal branch stars detected in M31 halo fields by Holland et al (1996).

We determined the mean I-band magnitude of the red clump by constructing the luminosity function for stars with $(V-I)_o \geq 0.7$ and performing a non-linear least squares fit with a function consisting of a gaussian (to represent the RC density) and a quadratic polynomial (to represent the background RGB density). We calculate $I_{RC} = 24.34 \pm 0.05$, corresponding to $M_I = -0.13 \pm 0.1$, and a fairly narrow width of $\sigma_{RC} = 0.15$. A simple gaussian fit in color yields $(V-I)_{RC} = 0.95$. Assuming a metallicity of -0.7 dex from the best-fitting RGB ridge line, the theoretical models of Girardi & Salaris (2001) indicate that a red clump this faint and this red is most consistent with a population which has a mean age of $\gtrsim 8$ Gyr (see their Figure 1). Younger populations (*eg.* $\lesssim 4-5$ Gyr) of this metallicity would produce clumps which are $\gtrsim 0.2-0.3$ mag brighter than our measurement and significantly greater than expected errors in our photometric zeropoint (~ 0.05 mag).

Additional evidence for a predominantly old-to-intermediate age stellar population is provided by the ratio of red clump to red giant stars, N(RC)/N(RGB), which for fixed metallicity and helium abundance, is higher in younger populations. We find N(RC)/N(RGB) $\lesssim 1$ in the M31 outer disk, a rather low value, which according to the models of Cole (1999) can be used to exclude mean ages of $\lesssim 3$ Gyr for the clump population. For ages higher than this, the variation of N(RC)/N(RGB) with age flattens out (see also Renzini 1994) and makes it impossible to draw further conclusions.

There is no compelling evidence for asymptotic giant branch stars above the tip of the red giant branch in the CMD which would represent the luminous shell He-burning descendants of young-to-intermediate age RC stars (2–6 Gyr). However as this evolutionary phase is extremely rapid, such stars would need to be present in very significant numbers to be detected given the small WFPC2 FOV (0.3 kpc^2 at distance of M31).

3.3. *The Blue Population*

In addition to the dominant red population, we also detect a very sparsely populated blue plume which extends to V~ 24, V−I ~ 0 and most likely represents main sequence stars with masses in the range $\sim 1.5-3$ $M_\odot$. The existence of these more massive stars is not surprising since our HST field lies within the outer HI disk (Newton & Emerson 1997) however the lack of a significant numbers of them means that little star formation has taken place in these parts over the last Gyr or so.

A tantalizing feature in the CMD is the population of faint stars which appears to connect the blue plume at V~ 25 to the RC. This feature could either represent the subgiant branch (SGB) of a ~ 1Gyr population, or else the extended blue horizontal branch (BHB) of ancient, very metal poor stars ($\gtrsim 10$ Gyr, [Fe/H] ~ -1.7). The SGB interpretation has difficulties with the large number of stars in this region compared to what would be the main sequence turnoff region (a factor of 2:1), given that for these ages/turnoff masses the ratio of time spent in the SGB phase relative to the main sequence phase is of order 1%. On the other hand, the magnitudes of these stars agree with the old BHB detected in the halo of M31 by Holland et al (1996) and indicated in Figure 3. While photometric errors and incompleteness (coupled with the sparseness of the field) hinder deciphering the true nature of this intriguing feature at present, we feel the available evidence best supports its identification as a trace population of very old, metal poor disk stars.

4. DISCUSSION & IMPLICATIONS

We have derived constraints on the mean age and metallicity of stars at large radii along the major axis of M31,

from the CMD morphology of the evolved stellar populations. The field analysed is the only deep HST/WFPC2 pointing to date which, based on extrapolating measured M31 structural parameters, samples the outer disk ($\gtrsim$ 3 disk scale lengths) without significant halo contamination.

The stellar population in this field is predominantly old-to-intermediate age (ie. $\gtrsim$ 8 Gyr) with a relatively high mean metallicity ([Fe/H]~ -0.7), indicating these stars formed from gas which was significantly pre-enriched. There is also a tenative detection of a trace population of ancient ($\geq$ 10 Gyr) metal-poor stars. These findings are difficult to reconcile with a scenario in which the formation of large disks is delayed to z$\lesssim$ 1, and suggest that attempts to solve the angular momentum problem with strong feedback are still missing an important aspect of galaxy formation. A considerable mean age for stars at large radii also limits the importance of late infall in the growth of the outer disk (eg. Ferguson & Clarke 2001)

Additional evidence exists to support the notion that large galactic disks have been in place for some time. This includes the finding by Brinchmann & Ellis (2000) that massive galaxies have formed most of their stellar mass before a redshift of unity, and the well-formed regular spiral galaxies at z$\sim$ 1 which appear in rest-frame optical images of the *Hubble Deep Field* (Ferguson, Dickinson & Williams 2000). Furthermore, study of gas in the extreme outer regions of nearby disks indicates prior chemical enrichment, most plausibly from previous generations of stars in these parts (Ferguson et al 1998).

On the other hand, there are alternative interpretations of our findings that have less serious implications for galaxy formation but which, at the present time, appear somewhat less likely. These include:

Disk Geometry: The outer gaseous and stellar disks of M31 warp beyond a radius of $\approx$ 20kpc (Newton & Emerson 1977, WK88), with the disk bending northwards at large radii along the north-east major axis. Inspection of the deep optical plates of WK88 reveals that our field is in the general direction of the warp and situated just below the so-called 'northern spur'. Thus while it may be that our field misses the brightest part of the stellar disk at this radius, it is projected close enough to it that a significant fraction of disk stars should still be detected.

Disk Structure: In calculating the expected disk-to-halo contribution at the location of the WFPC2 field, we have assumed the disk parameters determined by WK88 can be extrapolated beyond the region over which they were measured (R=0–20 kpc). If the disk surface brightness declines faster than this in the outer regions, then our calculation will overestimate the disk fraction. Although several galaxies have been reported to display significant declines in their surface brightness profiles at radii of 4–6 exponential scale lengths (*eg.* van der Kruit & Searle 1982), others continue to exhibit exponential behaviour out to 8-10 scale lengths (*eg.* Weiner et al 2000). A very severe decline in disk surface brightness would be required to render the halo stars dominant at the location of the WFPC2 field however.

Pollution from Tidal Debris: The recent discovery of a giant tidal stream of stars near the southern minor axis of M31 indicates that some fraction of the field halo population was not formed *in situ* but was accreted from presumably smaller subsystems (Ibata et al 2001). The similarity of the mean metallicity of stream stars, the halo field stars and those in the far outer disk, raises the intriguing possibility that these stars all have a common origin. We cannot, at present, rule of the presence of faint halo substructure in the vicinity of our WFPC2 field, but note that the recently-detected stream lies more than 120° away from this location.

This *Letter* illustrates the potential of detailed studies of resolved stellar populations in the local Universe to constrain the formation and early evolution of galaxies. With the commissioning of the Advanced Camera for Surveys (ACS) on HST later this year and the advent of adaptive optics on 8-m class telescopes, such studies may soon rival high redshift observations as direct tests of the galaxy assembly process.

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